Analysis of the Preparation-Storage-Use of Hydrogen

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Abstract: In the past few decades, the production of electricity generated by chemical fuels has always dominated, but the greenhouse gases produced by fossil fuels have become a major problem affecting the global climate. Therefore, hydrogen energy, as the clean energy most used by mankind at present, has extremely high exploration value. This article analyzes the use process of hydrogen energy in detail from three parts. First part is the preparation of hydrogen, second part is the storage of hydrogen, and the last is how to use hydrogen. Proton exchange membrane electrolyzer (PEMWE) technology is the main preparation technology of hydrogen energy use process, which uses photovoltaic power generation as the main source of electricity. In this article the principle of PEMWE's hydrogen production technology and technical components and functions of PEM electrolyzers, but also compare the more mature Proton exchange membrane (PEM) technology with the Anion exchange membrane (AEM) electrolyzed water technology with great potential in the future, and analyze the pros and cons of both. In terms of storage, this paper analyzes the advantages and disadvantages of gas compressed storage, liquid storage, metal hydride storage and underground storage. In terms of hydrogen energy treatment. Cogeneration technology, especially in hydrogen fuel cells, is the primary method for converting hydrogen into electricity, and the remaining hydrogen will play a role in different fields for different purposes.

1 INTRODUCTION

According to the "World Energy Statistical Yearbook 2023" report, primary energy consumption will increase in most regions of the world in 2022 (except Europe and the CIS). Despite rising prices for all three fossil fuels, natural gas, oil and coal, only natural gas has seen demand fall. Fossil fuels still account for 82% of the world's total energy supply (Energy institute, 2023). This will lead to the production of greenhouse gases, affecting climate change and global warming (Baroutaji et al., 2023). The increase in the share of renewable electricity generation has also become a significant trend, with renewable electricity (excluding hydropower) growing by 14% in 2022, meeting 84% of the net increase in electricity demand. In the 21st century, more and more people believe that hydrogen is an important energy source that can change the future energy system (Falcone, Hiete and Sapio, 2021). Hydrogen fuel cells are the green energy source most likely to make the "hydrogen economy" a reality (Cheng et al., 2007). The development potential of hydrogen energy is reflected in that it is a green, clean and pollution-free energy source. This article proposes a hydrogen energy usage process and analysis of hydrogen production-storage-power generation, with the purpose of using hydrogen energy in an environmentally friendly and energy-saving way. In the process of promoting the development of hydrogen energy utilization, scientific and reasonable measures should be taken to realize the dual benefits of economy and environment.

2 PEM ELECTROLYSIS WATER HYDROGEN PRODUCTION TECHNOLOGY

2.1 Technical Principle of Hydrogen Generation by PEM Electrolytic Water

The main hydrogen generation technologies of PEM are divided into two types as PEMFC and PEMWE.

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PEMFC hydrogen generation technology produces water as a byproduct of the chemical interaction between hydrogen and oxygen, which transforms chemical energy into electric energy (Baroutaji et al., 2023). The chemical principle of the latter PEMWE technology is as follows. The technical principle of PEMWE is to inject deionized water into an electrolytic cell, and the electrolytic cell consists of two parts, and a is used to separate the two parts. When an external power source is energized on the cell, water (H_2O) breaks down at the cathode and anode. The reaction formula of cathode and anode is shown below (Kya et al., 2020).

$$2H_2O_{(l)} \rightarrow O_{2(g)} + 4H^+_{(aq)} + 4e^- \; [E_{OX} = -1.23V] \quad (1)$$

$$2H^+_{(aq)} + 2e^- \rightarrow H_{2(g)} \; [E_{Red} = 0.00V] \quad (2)$$

Of the following two equations, formula (1) is called oxygen evolution reaction (ORE) and formula (2) is called hydrogen evolution reaction (HER). In an acidic environment, the total reaction composed of two half reactions is shown in formula (3). When a DC power supply is connected to the electrode and the applied voltage is higher than the thermodynamic potential, water begins to be decomposed (Falcão and Pinto, 2020).

Whole reaction:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (3)$$

In summary, the technical principle of PEMWE is that the cathode gains electrons to produce hydrogen, and the anode loses electrons to produce oxygen. The intermediate PEM (proton exchange membrane) plays two roles, one is to allow hydrogen ions to pass and block electrons, and the other is to separate hydrogen and oxygen to prevent mixing. And then end up with hydrogen and oxygen to collect as shown in figure 1.

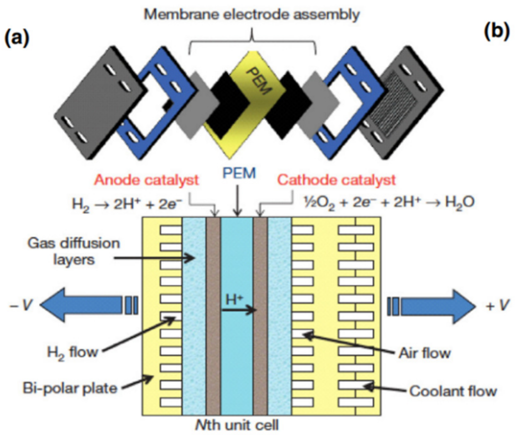

Figure 1: The structure of PEM fuel cell (Wang et al., 2020)

2.2 PEM Electrolysis Water Hydrogen Production Technology Components

In addition to the DC power supply on the top, there are four components in PEMWE electrolyzer device including Bipolar Plates (BPP), Gas Diffusion Layer (GDL), Catalyst Layer (CL) and Membrane, as shown in figure 2.

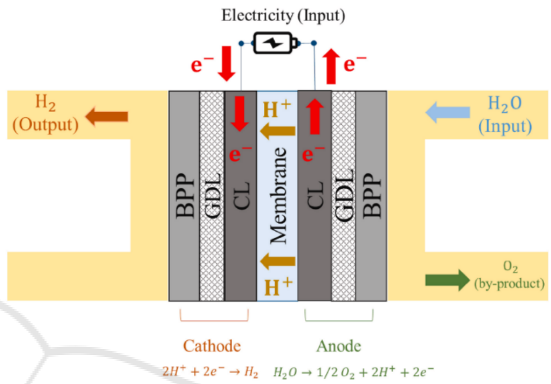

Figure 2: Main components and working principles of PEMWE (Baroutaji et al., 2023)

2.2.1 Bipolar Plate (BPP)

Also known as the collector plate, the main function of bipolar plate is to provide two channels of air flow and current conduction. The former serves to prevent hydrogen and oxygen from combining in the fuel electrolyzer, while the latter creates a channel for electricity to flow between the cathode and anode (Xiong et al., 2021). BPP is mainly divided into two types, one is a metal bipolar plate, one is a graphite bipolar plate. The main disadvantages of graphite bipolar plates are that their strength is low and the material is relatively fragile. The thickness of the material needs to be increased to ensure the strength of the material. However, increasing the thickness of the material will lead to the increase of the quality of the electrolyzer, which is not conducive to the conditions of lightweight and convenient transportation. In addition, the use condition of graphite bipolar plates is high-temperature graphitization treatment, which requires a long production cycle. Hence, the aforementioned shortcomings result in a subpar commercial impact of graphite bipolar plate. The raw materials of metal bipolar plates are usually corrosion-resistant metals, such as titanium, aluminum, nickel alloys. Despite challenges stemming from the acidic environment and corrosion by reducing substances like hydrogen and oxygen within the electrolytic cell, metal bipolar plates offer significant advantages including high strength, excellent conductivity, cost-effectiveness, and easy scalability in production. Hence, metal bipolar plates retain considerable application potential and commercial viability (Wang et al., 2020).

2.2.2 Gas Diffusion Layer (GDL)

Gas diffusion layer (GDL) is one component of PEM. Ensuring that the gas can diffuse evenly into the catalyst layer is the main goal of the gas diffusion layer. Its porous construction makes it possible for the gas to pass through and arrive at the intended location. GDL also has a certain degree of conductivity and thermal conductivity, which not only helps to maintain the normal flow of current in the electrolytic cell, but also helps to evenly distribute and diffuse the heat inside the electrolytic cell, thereby providing a suitable working temperature for the electrolytic cell. The mechanical strength of GDL provides support and protection for more fragile membranes and catalyst layers. Its structure can also drain the water by-product of the electrolyzer, and it ensures that moisture does not accumulate inside the electrode, thereby avoiding blocking the gas channel and affecting performance (Ozden et al., 2019).

2.2.3 Catalyst Layer (CL)

The specific position of the catalytic layer is attached to both ends of the proton exchange membrane, which is divided into a cathode catalytic layer and an anode catalytic layer. Currently, the cathode mainly uses platinum carbon (Pt/c) catalyst to accelerate the hydrogen evolution reaction (HER). The platinum-carbon catalyst is composed of platinum nanoparticles and carbon carrier, in which the platinum nanoparticles are efficient hydrogen precipitation catalysts, while the surface of the carbon carrier has more pores, which increases the surface area and stability of the catalyst. However, platinum-based catalysts have a higher cost than what, constituting approximately 35% of the total cost of PEMWE (Baroutaji et al., 2023). Iridium oxide (IrO_2), which has good oxygen evolution reaction (OER) activity and stability and can successfully encourage oxygen precipitation, is the primary material used in the anode. Reducing the activation energy needed for water electrolysis is the catalytic layer's purpose. As a result, the pace at which hydrogen and oxygen evolve is accelerated. Enhancing the electrolysis efficiency is possible by increasing the electrode's current density through the design and optimization of the catalytic layer. Lastly, the catalytic layer's strong chemical stability guarantees PEMWE's steady operation over the long run (Sui, Zhu and Djilali, 2019).

2.3 Comparison of Technology of PEM and AEM

In the field of producing hydrogen through water electrolysis, PEM and AEM technologies currently hold a dominant position. These two technologies differ in their features and benefits. The solid electrolyte utilized in PEM electrolysis cells ensures a high energy density and efficiency, which is PEM's advantage. As a result, PEM technology plays a big role in the field of producing hydrogen by water electrolysis. The benefit of AEM technology stems from the utilization of non-precious metal catalysts, which significantly reduces material costs and makes the implementation of AEM technology for hydrogen production via water electrolysis more economically feasible (Pushkareva et al., 2020). However, the current high cost has not affected the competitiveness of PEM technology, because of the technical maturity and wide application. The widespread application of PEM fuel cells provides rich experience and technical support for hydrogen production, further promoting the development of PEM technology. Although AEM technology has advantages in material cost, further efforts are still needed in terms of technology maturity and large-scale application (Santoro et al., 2022).

However, with the increasing focus on environmental awareness and the rapid advancement of renewable energy technologies, there is a growing demand for electrolytic water hydrogen production. This trend provides ample opportunities for the development of AEM technology in this field (Li and Baek, 2021). With its flexibility and low cost, AEM technology is expected to emerge as a key technology in future water electrolysis-based hydrogen production (C hina Energy News Network, 2024). In summary, PEM and AEM have their own advantages in hydrogen production technology through water electrolysis. PEM technology is favored for its high efficiency and maturity, while AEM technology shows great potential for its economy and flexibility. These two technologies will probably become increasingly significant in the field of hydrogen production by electrolytic water in the future as technology develops and application scenarios grow.

2.4 Source of Electricity for Hydrogen Production

2.4.1 Generating Electricity from Non-Renewable Sources

According to the report from the World Energy Statistics Review, global energy demand will grow by 1% in 2022, with a record growth in renewable energy. However, the dominant position of fossil fuels has not changed, making up 82% of the world's energy supply. Natural gas contributes 27% to the overall electricity generation from fossil fuel power globally (Leonard, Michaelides and Michaelides, 2020). However, coal still ranks first in the total power generation, accounting for approximately 35.4%.

2.4.2 Generating Electricity from Renewable Sources

According to data from British Petroleum's latest BP World Energy Outlook, by the end of April 2023, China had amassed a combined installed capacity of 820 GW from wind and solar power, constituting a substantial portion of the nation's total power generation capacity, which is 31% (Leonard, Michaelides and Michaelides, 2020). Of this 31% of total renewable energy capacity, wind power accounted for 14 percent, while solar power accounted for 17 %. Of the new installed capacity in 2023, wind added 14.2 GW and solar added 48 GW, which accounted for 16.8% and 57.2% of the new installed capacity, respectively. This data further indicates that China's installed capacity of renewable energy has increased by 11.5% year-on-year. By 2050, the share of wind and solar power in China's total power generation will increase from less than 10% today to more than 50%, and may even increase to more than 65%.

2.4.3 Cost Comparison

The cost of different method for hydrogen production is summarized in table 1. The cost of electrolyzing water is more than three times that of fossil fuels, making it expensive. Additionally, the electricity cost of electrolyzed water accounts for a significant proportion of the total cost (>50%).

Table 1: Production costs from various energy sources (China Energy Storage Network, 2024)

Traditional method	Cost of raw materials (dollars/kg)	Cost of hydrogen production (dollars/m3)
Coal	8.68-18.33	1.36-1.90
Natural gas	0.23-0.28（m3）	1.36-1.89
Electrolysis of water	Proportion of electricity consumption cost	Cost of hydrogen production (dollars/m^3)
Proton exchange membrane	50.52	5.54
Alkaline water electrolysis	74.91	5.54

3 HYDROGEN ENERGY STORAGE

3.1 Gaseous Compression Storage

Currently, among various hydrogen storage technologies, room temperature compressed gas hydrogen storage technology (CGH2) is the most mature one. More than 80% of the 215 hydrogen stations operating worldwide in 2010 used CGH2 technology. At present, the pressure of CGH2's on-board storage tank is as high as 70MPa, which changes the physical state of hydrogen and reduces the distance between gas molecules, thereby compressing and storing hydrogen into the hydrogen storage tank. CGH2 technology requires low equipment costs, high safety, and strong flexibility. The storage of compressed gas at room temperature is not limited by geographical location and climate conditions, and can be stored and transported in various environments. However, the bulk density of hydrogen does not increase with the increase of pressure, which makes it difficult to increase the density of hydrogen (Yanxing et al., 2019), and if the pressure is too large, it will also bring safety problems.

3.2 Liquid Storage

The operational principle of liquid storage technology (LH_2) is to use a compressor to compress hydrogen gas to extremely high pressure, thereby increasing gas density, and then reducing the temperature of high-pressure gas to -253 ℃ to achieve liquefaction. Compared to gaseous compression technique, liquid storage technology has a higher hydrogen density. High energy density and long-term stability are features of liquid storage technology. Because of its higher liquid storage density and comparatively stable physical characteristics, more hydrogen may be held in each container. Nevertheless, the liquefaction process is energy-intensive. It is inevitable that heat will enter the container, causing a hydrogen loss of 2% -3%. Therefore, liquid storage technology is more suitable for high-tech industries like the aerospace industry (which consider performance more than cost) (Yanxing et al., 2019).

3.3 Metal Hydride Storage

Metal hydride storage is the use of metal or alloy with hydrogen reaction to produce metal hydride, when hydrogen and metal or alloy contact, hydrogen atoms will enter the metal or alloy lattice, thus forming a stable compound, the metal hydride. Heating the compound until hydrogen is needed breaks the chemical bond between the hydrogen atoms and the metal, releasing hydrogen (Klopčič et al., 2023). Metal hydrides have small space requirements and strong ductility. Figure 3 lists the volume and weight energy density of different metal hydride hydrogen storage systems.

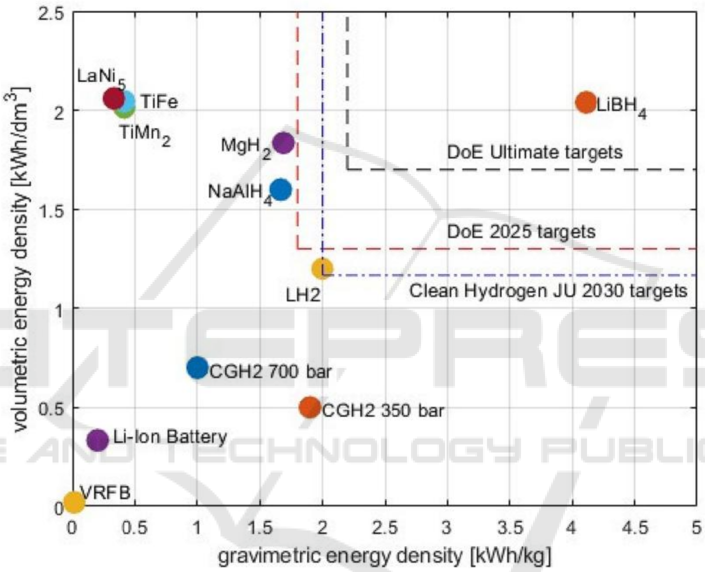

Figure 3. Volumetric and gravimetric energy densities of storage systems (Klopčič et al., 2023).

3.4 Ground Storage

In June 2019, underground storage was identified by the International Energy Agency (IEA) as the optimal storage mode for long-term and large-scale storage (Elberry et al., 2021). It is a method to store hydrogen by using the physical characteristics of underground space. The injection of hydrogen gas into the ground by drilling holes or pipelines into depleted oil and gas reservoirs, aquifers, or cave storage (excavation or dissolution of mined rock, such as salt coal, igneous and metamorphic rocks). These underground media have many pores and good permeability, and hydrogen enters underground materials through adsorption, dissolution, etc. A buffer gas such as N_2 or CH_4 is injected before hydrogen is injected. The buffer gas is periodically expanded and compressed to ensure the ground pressure and transportation rate required for transportation (Zivar et al., 2021). The underground hydrogen storage has a large capacity, long storage time, and strong safety, because the underground structure acts as a natural barrier, separating hydrogen from the outside world and greatly reducing risks. And this storage method does not produce harmful substances, making it more environmentally friendly.

4 HYDROGEN PROCESSING METHOD

4.1 Hydrogen Fuel Cell

Currently, hydrogen fuel cell technology primarily finds application in the realm of new energy vehicles. With zero emissions while using hydrogen and oxygen as fuel, PEMFC technology's cleanliness and environmental friendliness are its greatest advantages (Cheng et al., 2007). Combination of heat and power (CHP) is currently a mature technology suitable for industrial applications and large-scale commercial use for a high efficiency in power generation. Within the entire energy production and supply system, cogeneration utilizes the heat generated by fuel cells to generate electricity, which is then converted into low-grade thermal energy in power engineering, resulting in higher efficiency in the utilization of hydrogen energy. Therefore, the efficient and environmentally friendly energy utilization method combining the advantages of fuel cell and cogeneration has broad application prospects (Arsalis, 2019).

4.2 Analysis of Utilization Scenarios

Of the hydrogen production process, about 90% is currently used for ammonia synthesis, methanol production and refineries. This ratio will gradually decline over the next few years, until hydrogen production increases and this energy source is gradually combined with other energy sectors, such as for grid power generation (Tarhan and Çil, 2021). In the metallurgical, fertilizer, and chemical industries, as well as the processing and upgrading of crude oil, hydrogen has a very high commercial value. Additionally, it is important for fuel upgrading, aviation and marine fuels, and other sectors (Okolie et al., 2021).

5 CONCLUSION

PEMWE water electrolysis technology is now a very mature technology, has been widely used and studied. Further research on PEMWE is currently focused on the modeling of electrolyzers and the cost efficiency of electrocatalysts. In comparison with AEM electrolysis water technology, PEMWE currently has rich experience and market support. However, as the demand for hydrogen energy continues to rise, AEM electrolysis water technology that doesn't necessitate valuable metals as materials has shown advantages such as low cost and flexibility, and has greater potential in future. As for hydrogen storage, the selection of different storage technologies depends on different regions, different economic conditions, different technical differences and so on. This paper analyzes the advantages and disadvantages of four different storage technologies, namely gas compressed storage, liquid storage, metal hydride storage and underground storage, which should be comprehensively considered according to the requirements of specific application scenarios, safety, cost, efficiency and other factors, and make decisions based on the maturity and sustainability of the technology. Regarding the utilization of hydrogen energy, current hydrogen fuel cells are predominantly employed in the new energy automotive sector. The specific suggestion is to utilize the heat generated by PEMFC when converting hydrogen energy into electric energy and employing the CHP mode, the efficiency of hydrogen fuel cell utilization is greatly improved. The process of using renewable energy to generate electricity, producing hydrogen through PEMWE technology, and finally generating electricity through hydrogen fuel cells through cogeneration mode has the characteristics of sustainability, environmental protection, and efficiency, and has broad application prospects.

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